Resonant HH searches by ATLAS and CMS

Andres Tiko (INFN Padova) on behalf of ATLAS and CMS Collaborations
Status of current best results

Wide range of masses studied, no excess over background expectation

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 27.5 - 36.1 \text{ fb}^{-1} \)

arXiv:1811.09689
Outline

- Motivation and theoretical framework
- New results
- Searches included in combination
  - $b\overline{b}VV$
  - $b\overline{b}b\overline{b}$
  - $b\overline{b}\tau\tau$
  - $b\overline{b}\gamma\gamma$
- Combination
- Other results
- Prospects
Motivation and framework

- Several **BSM theories predict** the existence of heavy particles decaying into a pair of Higgs bosons.
- Various **models explored** with particles decaying to a Higgs boson pair:
  - **Spin-2 graviton**, as predicted in the Randall–Sundrum model of warped extra dimensions
  - **Spin-0 radion**
  - Models with two Higgs doublets (2HDMs)
- **Current** studies mostly focused on ggF production mode
- **Many decay channels** provide possibilities for various searches with diverse analysis techniques and sensitivities in different mass ranges
- A **combination** of channels needed to obtain the best possible sensitivity for the HH production
- Most searches use ≈36 fb⁻¹ 2016 or 2015+2016 data

Coloured logos show channels included in combination
New Results
Final states of **2SS, 3 and 4 leptons + MET and jets**

Assumption $m_X > 2m_H$ such that both $H$ are produced on-shell

Obs (exp) limits range from **9.3 (10) pb to 2.8 (2.6) pb**, with the smallest limit set for $m_X = 500$ GeV

**No excess** over SM backgrounds found

**Limits also** set for new scalar bosons in the process $X \rightarrow SS \rightarrow WW(*)$
**bbZZ* decays in the bblvνν final state – CMS**

On-shell Z boson decays to **e+e- or μ+μ- pairs**, \(m_{ll} > 76\,\text{GeV}\) for orthogonality with b\(b\)VV search

The **other Z boson** can be off-shell, decays to **neutrinos**

Signal and control regions defined using \(m_{bb}\) and \(m_{ll}\)

- Main backgrounds **t\(t\)** and **DY**
- Two **BDTs** trained, above and below \(m_X = 450\,\text{GeV}\)

Limits for radion and graviton by:

- Binned ML fit of the **pseudo-\(M_T(HH)\)**
- Simultaneously in the signal and control regions for combined e+e- and μ+μ-

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CMS-PAS-HIG-17-032
Semileptonic decays of WW* considered:

Resolved and boosted modes for $H \rightarrow b\bar{b}$ decay

Control regions outside [100, 140] GeV window for $m_{b\bar{b}}$ to normalize and validate the estimate of the main $t\bar{t}$ background

Kinematic selection suppresses $t\bar{t}$ background, optimized for a spin-0 signal, limits also for spin-2

Limits from a ML fit to the $m_{HH}$ distribution simultaneously in signal and control regions, with combined electron and muon channels

No excess over background expectation found

arXiv:1811.04671
Results included in combination
**bbVV - CMS**

Includes two processes:
- **HH → bbWW → bbl+νl-ν**
- **HH → bbZZ → bbl+l-νν**

Primary focus on bbWW

12 < \(m_{ll}\) < \(m_Z - 15\) GeV cut to suppress backgrounds:
- Negligible impact on H → WW decays
- Removes the subset of H → ZZ with on-shell Z(\(ll\)), covered by bbZZ analysis shown previously

A **DNN** is used to improve rejection of large t\(t\) and DY backgrounds, parametrized according to the mass of the resonance

DNN output for ML fit, setting limits
Most sensitive channel for ATLAS for high masses
- Predominant **multijet background** estimated from data
- **Background normalizations** for multijet and $t\bar{t}$ determined with simultaneous fits in sideband region
- Profile-likelihood fit of $m_{HH}$ to extract the signal
- **2 analyses**, combined in mass range 800-1400 GeV

**Resolved analysis**, optimized for low $m_{HH}$:
- 4 resolved b-tagged jets, combined to 2 Higgs candidates with masses close to $m_H$
- Uses 27.5 fb$^{-1}$ of data, reduced luminosity from a problem in online b-tagging

**Boosted analysis**
- 2 large-area jets each with $\geq 1$ b-tagged track-jets and mass compatible with $m_H$.
- Full 2015+2016 dataset

Limits set for a narrow-width scalar and a spin-2 KK RS graviton model with $k/M_{pl} = 1$ or $k/M_{pl} = 2$.
Slight excess for scalar at 280 GeV
**b\overline{b}b\overline{b} - CMS**

3 *optimized searches* for different masses

- **Low mass** ($M_X < 0.7$ TeV)  
  - 4 b-tagged jets are required
  - 2 mass regions, 260-620 and 550-1200 GeV
  - Regression techniques to improve mass resolution

- **High-mass** ($M_X > 1.2$ TeV)  
  - 2 boosted H jets, double-b tagger
  - Jet substructure and flavor tagging techniques
  - Reduced invariant mass $m_{jj} - (m_{j1} - m_H) - (m_{j2} - m_H)$ used for fitting

- **Intermediate mass** (0.7–1.2 TeV)  
  - Both fully resolved final state and the one with a H jet and two b jets
  - Parametric models for signal and background
  - Dominant background from QCD multijet events estimated using data sideband regions
  - Similar sensitivity as ATLAS, but better at low masses
  - Deficit where ATLAS sees excess

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**arXiv:1808.01473**
**b\bar{b}\tau\tau** - semileptonic and fully hadronic

**Most sensitive channel for ATLAS for low masses (<400 GeV)**
- Final states of
  - 1 e/\mu and 1 hadronic \(\tau\)
  - OR 2 hadronic \(\tau\) candidates
- Together with 2 b-tagged jets and MET
- BDTs for signal/bkg separation
- Profile-likelihood fit applied to the BDT distributions in 3 signal regions (hadronic, 2 SL with different triggers) and to event yields in a CR for Z+hf

305 < \(m_X\) < 402 GeV for \(\tan\beta = 2\) excluded for hMSSM

Gravitons excluded
325 GeV < \(m_{G\kappa\kappa}\) < 885 GeV, assuming \(k/M_{Pl} = 1\)

**Categories of 1 or 2 b-tagged jets, dedicated category for events with a boosted H jet candidate**

**Selection based on** \(m_{\tau\tau}\) and \(m_{b\bar{b}}\)
- BDT in the resolved semileptonic channels to reduce \(t\bar{t}\) background
- Likelihood technique for \(m_{\tau\tau}\) and kinematic fit for \(m_{\tau\tau b\bar{b}}\) reconstruction
- Binned ML fit performed simultaneously in the signal regions

Limits set for narrow resonance in range 250 < \(m_S\) < 900 GeV

Interpreted in hMSSM context,
2D exclusion of 230 < \(m_A\) < 360 GeV and \(\tan\beta \leq 2\)

Event categories with either 2 b jets or 1 tight b jet and another jet selected by BDT

Additional \textbf{kinematical selection}, different for masses over/under 500 GeV

\textbf{Signal} extracted from $m_{\gamma\gamma jj}$ spectrum by fitting a peak superimposed on a smoothly changing background

$m_{\gamma\gamma}$ mass required to be within 4.7(4.3) GeV of $m_H$

Observed \textbf{limits} range from \textbf{1.1 to 0.12 pb} over the mass range (without branching fraction $\approx 0.26\%$)

\begin{itemize}
  \item Most sensitive channel in CMS at low masses thanks to $\gamma\gamma$ mass resolution ($\approx 1.6$ GeV)
  \item Two different BDTs trained for corrected inv. mass $M_X$ over/under 600 GeV, strategy maximizes the sensitivity to the massive resonances
  \item 2D fit of $m_{\gamma\gamma}$ and $m_{bb}$ in categories of BDT value and $M_X$ mass window, background estimated from mass sidebands.
  \item Excluded cross sections of \textbf{4.2 to 0.23 fb} depending on $m_X$ and the spin hypothesis.
  \item Limits set for radion and graviton models
\end{itemize}
Combination

\( \bar{b}b\bar{b}b, \bar{b}b\tau\tau, \bar{b}b\gamma\gamma \) channels

Mass range 260–1000 GeV

Limits set for:

- Heavy scalar S with narrow width: 0.83 pb – 0.02 pb
- Spin-2 KK graviton with a width of 3-25% depending on mass and \( k/M_{pl} \)

\( \bar{b}b\bar{b}b, \bar{b}b\tau\tau, \bar{b}b\gamma\gamma, \bar{b}bVV \) channels

Mass range 250-3000 GeV

Under hypothesis of a narrow-width resonance, no significant excess for either a spin-0 or a spin-2 particle

ATLAS-CONF-2018-043

arXiv:1811.09689
Other results

**ATLAS** $\gamma\gamma WW^*, WW^* \rightarrow l\nu qq$

Event selection based on properties of final state objects:
- 1 e or $\mu$
- 2 light jets
- 2 photons

Benefits from excellent resolution of $m_{\gamma\gamma}$, used to fit signal and background yields

**CMS high mass $bb\tau\tau$**

Boosted large-cone jets

Dedicated $H \rightarrow bb$ tagging techniques for substructure

Reconstruction techniques specifically optimized to select events in which the tau pair is highly boosted

Results obtained from a combined fit to $m_{HH}$ distribution

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arXiv:1807.08567

arXiv:1808.01365
Studies for HL-LHC: b\(\bar{b}\)\(\bar{b}\)\(\bar{b}\)

Boosted analysis with large-radius jets

- Signal and background \(m_{HH}\) distributions taken from the most recent ATLAS analysis at 13 TeV, scaled to 3000 fb\(^{-1}\)
- Simulations used to derive mass-dependent scaling functions to extrapolate 13 TeV to 14 TeV
- Simulated distributions used to reproduce the impact of additional selection criteria not used at 13 TeV
- Systematic uncertainties scaled down by factors of \(\geq 2\) (where applicable) relative to 13 TeV to account for increased precision with 3000 fb\(^{-1}\)

Projection from 2015 b\(\bar{b}\)\(\bar{b}\)\(\bar{b}\) analysis

- Theoretical uncertainties are scaled down by a factor \(\frac{1}{2}\)
- Experimental systematic uncertainties are scaled down by the square root of \(L\) until lower limit based on achievable accuracy estimates with the upgraded detector
- Effects of higher pileup conditions and detector upgrades not taken into account

<table>
<thead>
<tr>
<th>(m_X) (TeV)</th>
<th>Median expected limits on (\sigma) (fb)</th>
<th>(\sigma^{NLO}_{\Lambda}) (1 TeV) (fb)</th>
<th>(\Lambda) (TeV) excluded</th>
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<td>0.3</td>
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<td>41</td>
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<td>0.7</td>
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<tr>
<td>1.0</td>
<td>4.4</td>
<td>2.4</td>
<td>190</td>
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</tbody>
</table>

VBF analysis

\(pp \rightarrow Xq\bar{q}, X \rightarrow HH \rightarrow b\bar{b}b\bar{b}\):

Higgs bosons highly boosted, reconstructed as large-area jets
Two energetic jets in the forward regions of the detector
Expected significance for gravitons assuming \(\sigma\)s of 1 fb

ATL-PHYS-PUB-2018-028

CMS-PAS-FTR-16-002

CMS-PAS-FTR-18-003

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HH resonant searches
Conclusions

- Rich research programme to search for HH resonant production underway at ATLAS and CMS
- Many different analyses performed
- No sign of New Physics so far over a range of resonance masses from 250 to 3000 GeV
- Challenging process to observe, more data needed
- Looking forward to results with full Run2 dataset appearing in the next years
- Analysis techniques continuously improving
- New final states to be added to cover also smaller corners of the phase space
Questions for theorists

It would be good to agree on common theoretical models to search for with ATLAS and CMS

Are the current models useful for theorists?
If not, which models would be good to look at or add to the current ones?

A white paper in preparation as a result of Double Higgs Production at Colliders Workshop
https://indico.cern.ch/event/731450/, where this is also discussed

One case could be signals where there is interference between resonant and nonresonant production

What would be good models for new heavy scalars?
Backup
Combined limits

**ATLAS Preliminary**

\[ \bar{s} = 13 \text{ TeV}, \ 27.5 - 36.1 \text{ fb}^{-1} \]

**Spin-2, \ k/\sqrt{M_{Pl}} = 1.0**

**ATLAS Preliminary**

\[ \bar{s} = 13 \text{ TeV}, \ 27.5 - 36.1 \text{ fb}^{-1} \]

**Spin-2, \ k/\sqrt{M_{Pl}} = 2.0**

**CMS supplementary**

\[ \text{35.9 fb}^{-1} (13 \text{ TeV}) \]

Spin 2
- Observed
- Median expected
- 68% expected
- 95% expected
In the extended Higgs sector model $X \rightarrow SS$ is assumed to be the dominant $X$ decay mode. Looking at masses:

**270 GeV < $m_X$ < $2m_t$,** so that:
- $m_X > 2m_t$, where $X \rightarrow t\bar{t}$ is expected to dominate, is not considered

**135 GeV < $m_S$ < $m_X/2$,** so that:
- $S \rightarrow WW(*)$ is the dominant decay mode
- Both $S$ bosons are produced on-shell

The observed (expected) limits range from **2.5 (2.5) pb to 0.16 (0.17) pb**, with the smallest limit set for $m_X = 340$ GeV and $m_S = 165$ GeV.
Radion search (spin 0), 300 GeV mass hypothesis, $\mu^+\mu^-$ channel

**BDT cut** is at 0.7 (in SR only)

Pseudo-$M_T$(HH) distributions for signal and control regions
**b\bar{b}WW - ATLAS**

**ATLAS**

$\sqrt{s} = 13$ TeV, $36.1$ fb$^{-1}$

$HH \rightarrow b\bar{b}WW^* \rightarrow b\bar{b}lvqq$

low-mass, $m_X = 1000$ GeV

**Events/215 GeV**

- Data
- Rescaled $G_{K^0}(c=1.0)$
- Rescaled $G_{K^0}(c=2.0)$
- Rescaled Scalar
- Other
- Multijet
- W+jets
- $t\bar{t}$
- MC Stat + Syst Unc.

**ATLAS**

$\sqrt{s} = 13$ TeV, $36.1$ fb$^{-1}$

$HH \rightarrow b\bar{b}WW^* \rightarrow b\bar{b}lvqq$

high-mass, $m_X = 2000$ GeV

**Events/230 GeV**

- Data
- Rescaled $G_{K^0}(c=1.0)$
- Rescaled $G_{K^0}(c=2.0)$
- Rescaled Scalar
- Other
- Multijet
- W+jets
- $t\bar{t}$
- MC Stat + Syst Unc.
**HH resonant searches**

**ATLAS**

- $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
- 1 b-tag, loose selection

- $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
- 2 b-tag, loose selection

- $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
- 1 b-tag, tight selection

- $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
- 2 b-tag, tight selection
Exclusions for radion resonances:
- Assuming $\Lambda_R = 2\text{ TeV}$, for $m_X < 840\text{ GeV}$
- Assuming $\Lambda_R = 3\text{ TeV}$, for $m_X < 540\text{ GeV}$.

Exclusions for gravitons:
- Assuming $k/M_{pl} = 1.0$, gravitons are excluded in the range $290 < m_X < 810\text{ GeV}$
- Assuming $k/M_{pl} = 0.5$, the exclusion range is $350 < m_X < 530\text{ GeV}$. 
Exclusions for bulk RS models:

- Assuming $k/M_{pl} = 1$, gravitons are excluded in the range $313 < m_X < 1362$ GeV.
- Assuming $k/M_{pl} = 2$, the exclusion range is $m_X < 1744$ GeV.

Low mass limits are stronger for the wider graviton model because in the former the signal has a larger acceptance and the distorted shape peaks at higher values of $m_{4j}$ above a steeply falling background.
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HH resonant searches
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HH resonant searches
**HH resonant searches**

- **Resolved 1b1j** $\tau_\nu \tau_\nu$ channel
  - Data
  - Top
  - Multijet
  - Drell-Yan
  - Other bkg.
  - SM Higgs boson
  - Bkg. uncertainty
  - $m_H = 270$ GeV
  - $\sigma(gg + S) \times (S + HH) = 10$ pb

- **Resolved 2b** $\tau_\nu \tau_\nu$ channel
  - Data
  - Top
  - Multijet
  - Drell-Yan
  - Other bkg.
  - SM Higgs boson
  - Bkg. uncertainty
  - $m_H = 750$ GeV
  - $\sigma(gg + S) \times (S + HH) = 1$ pb

- **Boosted** $\tau_\nu \tau_\nu$ channel
  - Data
  - Top
  - Multijet
  - Drell-Yan
  - Other bkg.
  - SM Higgs boson
  - Bkg. uncertainty
  - $m_H = 750$ GeV
  - $\sigma(gg + S) \times (S + HH) = 0.5$ pb

**CMS**

- 35.9 fb$^{-1}$ (13 TeV)